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CHARACTERIZATION AND MODELING OF BONDED PIEZOELECTRIC SENSOR PERFORMANCE AND DURABILITY IN SIMULATED AIRCRAFT ENVIRONMENTS (PREPRINT)

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14. ABSTRACT
The performance characteristics of surface-bonded piezoelectric sensors were studied under accelerated exposure conditions typically found in operational aircraft environments. In particular, sensor performance was studied for freeze-thaw, elevated heat levels, electrochemical attack, substrate bend and tensile strains, and dynamic vibration conditions.

Evidence of both gradual and abrupt sensor performance degradation was experimentally observed due to undesired load transfer processes, which resulted in adverse sensor disbond and cracking events. Models were developed to better understand the critical shear-strain and viscoelastic conditions present in a typical surface-bonded sensor system, which permitted key material parameters related to bond and piezoelectric material type to be identified. Preliminary results will be presented for making improved bonded sensor system design choices based on the long-term exposure conditions expected in typical aircraft flight environments. Future activities are focused on verifying system performance using accelerated environmental testing, with the ultimate goal of improving the durability and survivability of surface-bonded piezoelectric sensor systems in typical aerospace environments.

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Characterization and Modeling of Bonded Piezoelectric Sensor Performance and Durability in Simulated Aircraft Environments

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ABSTRACT

A key question which needs to be addressed and answered with regard to successfully implementing structural health monitoring technologies involves the long-term operability, durability, and survivability of integrated sensor systems and their associated hardware. This is particularly true for structural health monitoring in aerospace systems, where integrated sensors are expected to perform and function effectively for many years under widely varying environmental conditions. In this research effort, the performance characteristics of surface-bonded piezoelectric sensors were studied under accelerated exposure conditions typically found in operational aircraft environments. Evidence of both gradual and abrupt sensor performance degradation was experimentally observed due to undesired load transfer processes between the substrate material and the sensor, which resulted in sensor disbond and cracking events. Models were developed to better understand the critical shear-strain and viscoelastic conditions present in a typical surface-bonded sensor system, which permitted key material parameters related to bond and piezoelectric material type to be identified. It is hoped that the results will help in making improved bonded sensor system design choices based on the long-term exposure conditions expected in typical aircraft flight environments.

INTRODUCTION

For aerospace systems, the use of structural health monitoring (SHM) as part of a larger integrated systems health management (ISHM) strategy offers the potential for monitoring the structural health of an aircraft system with far-reaching consequences and benefits [1]. By continuously monitoring the structural integrity of an aerospace system, ISHM systems will provide an unprecedented means for detecting, tracking, diagnosing, and predicting damage states within aircraft and spacecraft systems. This, in turn, will result in more efficient and effective maintenance, increased flight safety, increased asset availability, and improved performance levels.

A critical component of the aerospace health monitoring system involves the use of integrated sensors to interrogate and diagnose the health state of a structure. Three major types of sensor systems have been proposed for ISHM including: 1) surface

bonded sensors on existing structures, 2) integrated sensors within newly fabricated aerospace components, and 3) smart, self-sensing, multi-functional materials [2-4]. In all three cases, the integrated sensors become a part of the structure, and are therefore subjected to the dynamic stress conditions existing in an operational aircraft or space environment. If not accounted for, these in-service conditions can have an adverse affect on the performance of the sensor system regarding long-term durability, survivability, and operational performance of the system over extended time periods.

Previously published work [5-8] has shown that the performance of a surface-bonded piezoelectric sensor can degrade due to environmental stresses, resulting in undesired sensor disbond and cracking events. In this research effort, several representative examples of environmentally-induced damage to surface-bonded piezoelectric sensor disks are provided. A basic analysis of the stress-strain relationships for a bonded sensor system is also developed. The analysis considers the stresses induced in an adhesively bonded sensor from stress fields existing in an underlying substrate. In particular, the load transfer mechanism from the substrate through the adhesive layer into the sensor is studied. The relative stiffness ratios between the substrate and sensor materials, and the viscoelastic properties of the adhesive layer were found to be key parameters with regard to improving load transfer conditions, stress-strain conditions within the sensor, and ultimately sensor durability.

SURFACE-BONDED SENSOR DURABILITY STUDIES

Several researchers have recently begun to study the durability and long-term performance of surface bonded piezoelectric sensors [5-8]. Piezoelectric materials are naturally brittle, and therefore require special care with regard to understanding their performance features and potential failure modes and damage mechanisms. Figure 1 provides three examples of piezoelectric sensor performance for thin wafer disks attached to a thin aluminum panel. The measurements results depicted in Figure 1 were obtained using a noncontact displacement-field imaging technique [9,10], which provides a measure of the out-of-plane motions for the piezoelectric disks as gray-level images. Figure 1a provides an example of a normally functioning, non-damaged piezo disk, while Figures 1b and 1c provide examples of damaged piezo disks with sensor cracking and disbond, respectively. The crack and disbond locations appear as bright regions in the images, which indicates larger motion levels (out-of-plane) in those locations. The crack is easily imaged due to near-field ultrasound and free-boundary motion effects [9], while the disbonds are imaged as modal vibration lobe patterns, again due to free-boundary motion effects in the disbond region.

In the sensor cracking case (Figure 1b), the sensor was damaged during the installation process due to uneven pressure being applied to the sensor during the bond procedure. In the sensor disbond case (Figure 1c) , the sensor was not fully bonded across its entire surface, again due to inadequate uniform pressure being applied to the sensor during its application to the substrate material surface. In both damaged cases depicted in Figure 1, edge-disbond effects can also be seen around the entire perimeter of both piezo disks, again produced from inadequate pressure being applied in the bond installation process in those regions of the piezo disk material.
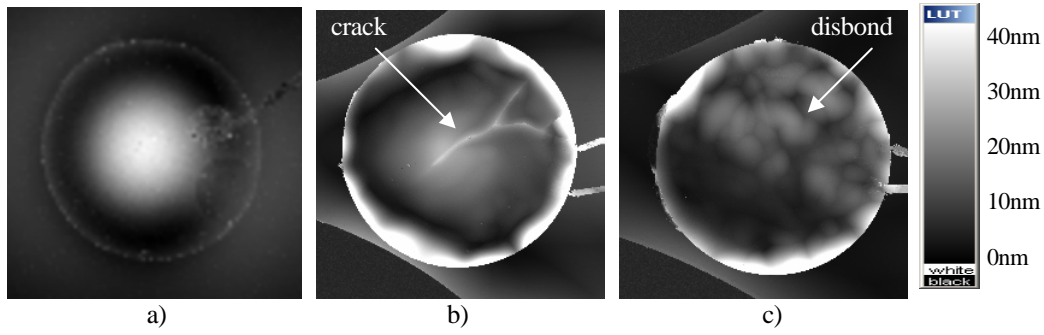
Figure 1. Displacement-field images of bonded piezoelectric disks: a) normal , b) cracked, c) disbonded.

In addition to the sensor installation damage depicted in Figures 1b and 1c, several cyclic exposure assessments have been attempted previously to understand the long-term performance characteristics of surface-bonded piezoelectric sensors for simulated aircraft environments [6-8]. The major results of an elevated temperature cycling experiment are depicted in Figure 2 for cracking and disbond occurring in piezoelectric sensor disks repeatedly exposed to 175°F temperature environments. For this particular study, a 12"x12" aluminum panel with a single piezoelectric sensor disk bonded in its center was exposed to repeated elevated heating conditions for 1-hour cycle durations.
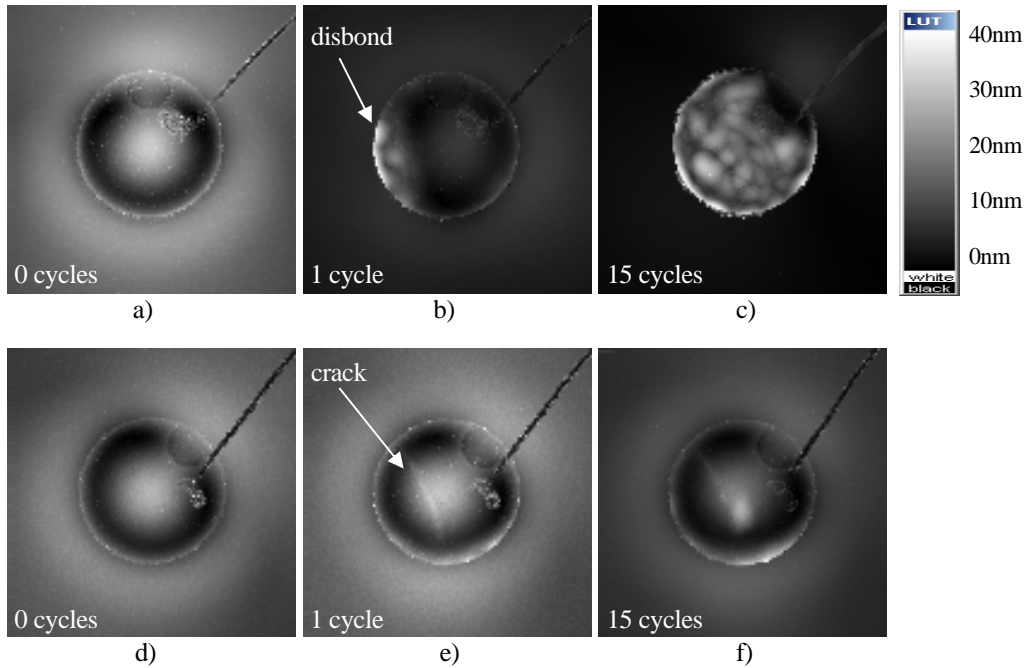

Figure 2. Displacement-field images of bonded piezoelectric disks subjected to repeated heat cycles: a) sensor 1 with zero heat cycles, b) sensor 1 with one heat cycle, c) sensor 1 with 15 heat cycles, d) sensor 2 with zero heat cycles, e) sensor 2 with one heat cycle, and f) sensor 2 with 15 heat cycles.

As shown in the figure, sensor disbond (Figure 2b) and sensor cracking (Figure 2e) occurred after a single heat-cycle event. As additional heat-cycle events were continued, the damage progressed and worsened. Figure 2c shows a progression of the

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disbond conditions from a localized edge disbond event to a disbond of the entire bond surface by 15 heat cycle exposures. In this particular case, the piezoelectric sensor became completely disbonded and lost its functioning capability after 20 heat cycles. In Figure 2f, the crack indicated in Figure 2e has begun to involve both cracking and disbond damage. As described in references 8 and 9, the disbond and crack damage can be explained by thermally-induced stress and strain conditions which had occurred primarily due to coefficient of thermal expansion mismatch between the sensor material (PZT-5A ceramic) and the substrate material (aluminum 2024-T3).

A critical aspect of the surface-bonded sensor system involves the type of adhesive used to bond the sensor to the substrate material. In the case depicted in Figures 1 and 2 above, the piezoelectric sensor disks were bonded to the aluminum panels using very a thin layer (~1-10 microns thick) of standard strain gauge bond adhesive (M-Bond 200 cyanacrylate and catalyst). The use of this particular adhesive material was motivated by the fact that is traditionally used in large-scale fatigue testing studies to understand stress-strain conditions occurring in aircraft life-testing efforts using accelerated vibration and load conditions for typical aircraft structures. For strain gauge measurements, the desired performance features of the adhesive are to transfer load efficiently to the surface-bonded strain gauge sensor system. This requires that the strain gauge adhesive cure as a stiff, rigid bond material.

For piezoelectric surface-bonded sensor applications, the opposite is actually true. For bonded ceramic sensor disks, it is desired that minimal load transfer occur between the substrate material and the sensor material. This requirement would mean that a more compliant adhesive bond material be used as described in the following analytic analysis section. With regard to coefficient of thermal expansion mismatch, the desire is to have a bond material that will provide a means for the sensor and the substrate to expand and contract without stress-strain load transfer between the two – again with the adhesive having a more compliant, flexible material property as temperature cycling occurs.

STRESS ANALYSIS FOR BONDED PIEZOELECTRIC SENSOR DISKS

The experimental results presented in the previous section provide evidence that surface-bonded sensors can be subjected to stress-strain conditions in a typical aircraft environment which can result in sensor damage and sensing performance degradation. Using a modified version of a one-dimensional theory of bonded joints developed by Rose [10], the load transfer between a surface-bonded sensor and a substrate material can be modeled as a shear loading process through the adhesive layer as shown in Figure 3. In this theory, the adhesive layer acts as a shear spring with the relationship for the adhesive shear stress given by:

$$\tau_a(y) = G_a\gamma_a = (G_a/t_a)[u1(y) - u2(y)], \tag{1}$$

where G_a is the adhesive shear modulus, γ_a is the adhesive shear strain, and t_a is the adhesive layer thickness. The shear tractions exerted by the adhesive can be replaced by an equivalent body force distributed uniformly across the thickness of each adherent, leading to the differential equilibrium equations:

$$t_p\sigma'_p = -t_r\sigma'_r(y) = \tau_a(y), \tag{2}$$
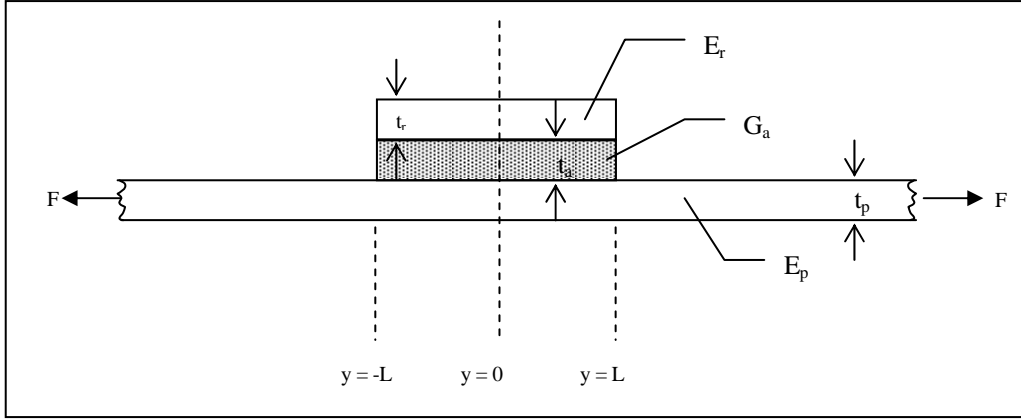
$$\tau''_a(y) - \beta^2\tau_a(y) = 0. \tag{3}$$

Figure 3. Adhesively bonded sensor geometry.

By applying the appropriate boundary conditions, the solution for this problem is found over the domain ($-L <= y <= L$):

$$\tau'_a(-L) = (G_a/t_a)\{(\sigma_p(0)/E_p) - (\sigma_r(0)/E_r)\} = (G_a/t_a)\{(F/E_pt_p) - 0\}, \tag{4}$$

$$\tau'_a(L) = (G_a/t_a)\{(\sigma_p(L)/E_p) - (\sigma_r(L)/E_r)\} = (G_a/t_a)\{(F/E_pt_p) - 0\}, \tag{5}$$

where the equation for β^2 is given by:

$$\beta^2 = (G_a/t_a)\{(1/E_pt_p) + (1/E_rt_r)\}. \tag{6}$$

The relations between the derivatives of the normal stresses and the shear stress can be integrated to give:

$$\sigma_p(y) = \sigma_p(-L) + (1/\beta t_p) \{ 2A(cosh(\beta y) - cosh(-\beta L))\} =$$

$$\sigma_r(y) = \sigma_r(-L) + (1/\beta t_r) \{-2A(cosh(\beta y) - cosh(-\beta L))\} \tag{7}$$

$$= (F/E_pt_p)) (G_a/t_a) (1/\beta^2 t_r\, cosh(\beta L)))((cosh(\beta y) - cosh(-\beta L))).$$

The stress conditions in the sensor can be expressed in terms of a stiffness ratio as:

$$\sigma_r(y) = [FS/((1+S)t_r)][1 - \{ cosh(\beta y)/cosh(\beta L)\}]$$
$$= \sigma_r(sp)[1 - \{ cosh(\beta y)/cosh(\beta L)\}], \tag{8}$$

where S is the stiffness ratio defined by:

$$S = (E_rt_r/E_pt_p). \tag{9}$$

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The maximum stress value in the sensor is at the center, *(y=0)*, and is given by:

$$\sigma_r(0) = \sigma_r(sp)[\ 1 - \{\ 1/\cosh(\beta L)\}]. \tag{10}$$

It is also observed that:

$$\lim_{\beta L \to \infty} \sigma_r(0) = \sigma_r(sp), \tag{11}$$

and that:

$$\lim_{\beta L \to 0} \sigma_r(0) = 0. \tag{12}$$

If the shear modulus becomes infinite, or the adhesive layer thickness becomes infinitesimal, then the stress distribution in the sensor is can be written:

$$\sigma_r(y) = [FS/((1+S)t_r)][H(y+L) - H(y-L)], \tag{13}$$

and the shear stress distribution in the adhesive interface layer can be written as:

$$\tau_a(y) = -t_r\sigma'_r(y) = -[FS/((1+S))][\delta(y+L) - \delta(y-L)]. \tag{14}$$

Using Equation (8), the stress conditions in a surface-bonded sensor for compliant, rigid, and infinitely rigid bonds can be calculated (Figure 4a), with parameters of: $E_p = 7.31 \times 10^{10}$ Pa, $E_r = 8.40 \times 10^{10}$ Pa, $G_a = (7.00 \times 10^6$ Pa for compliant, 7.00×10^8 Pa for rigid, and Infinite), $t_p = .001$ m, $t_r = 0.0001$ m, $t_a = 0.0001$ m, $L = .005$m. In order to lower stress transfer between the substrate and the sensor, the size of the sensor or adhesive shear modulus must be decreased, the adhesive layer thickness must be increased, or the stiffness ratio must be decreased.

Using Equation (14), the adhesive shear stress for a compliant and rigid bond can be calculated (Figure 4b). From Figure 4, it is clear that the use of a compliant bond helps with load/stress transfer to the sensor, and also with shear stress levels in the adhesive layer, which both help enhance sensor durability and bond integrity.

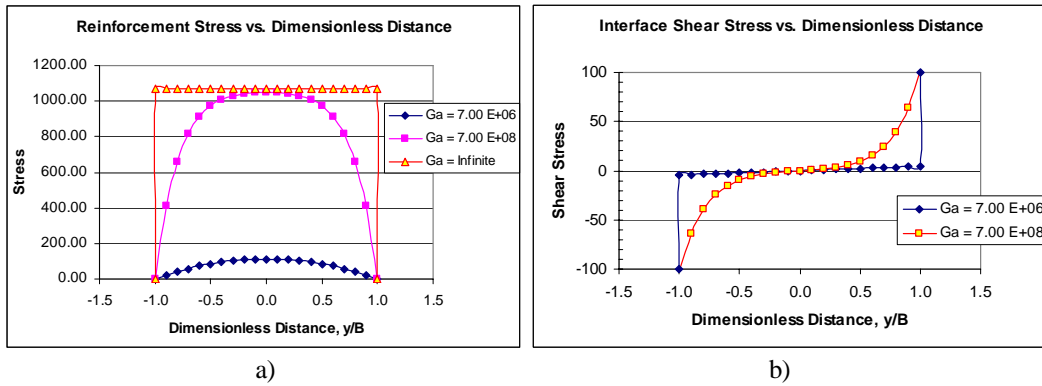a)   b)

Figure 4. a) Sensor stress distribution for 1.0 N/m unit lineal load with compliant, rigid, and infinitely rigid bond conditions, and b) interface shear stress distribution for 1.0 N/m unit lineal load for compliant and rigid bond conditions.

CONCLUSIONS

The long-term performance of integrated sensor systems represents a critical aspect of integrated systems health management (ISHM). Environmental effects due to temperature cycling, outdoor exposure, electrochemical exposure, and dynamic vibrations in particular can have a significant impact on the general performance of surface-bonded and fully-integrated sensor systems. In this research effort, the performance characteristics of surface-bonded piezoelectric sensors were studied under accelerated exposure conditions typically found in operational aircraft environments. Evidence of sensor performance degradation was experimentally observed due to undesired load transfer processes, which resulted in sensor disbond and cracking events. Models were developed to better understand the critical shear-strain and viscoelastic conditions present in a typical surface-bonded sensor system, which permitted key material parameters related to bond and piezoelectric material type to be identified. Analytic model results showed the partitioning of load between the substrate and sensor as being dependent on the relative stiffness between the two materials. Regarding the influence of the adhesive material layer, the load was found to be asymptotically transferred into the sensor from its edge interface, moving toward the center of the sensor at a rate determined by the shear modulus and thickness of the adhesive, the substrate stiffness, and the sensor thickness.

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